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# Typical Repository Conditions for Generic Commercial and Defense High-Level Nuclear Waste and Spent Fuel Repositories in Crystalline Rock

Technical Report

January 1986

Reference Repository Conditions
Interface Working Group

prepared for

Office of Crystalline Repository Development
Battelle Memorial Institute
505 King Avenue
Columbus, OH 43201-2693

OCRD
Office of Crystalline Repository Development

BATTELLE Project Management Division

## BIBLIOGRAPHIC DATA

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To: Distribution of BMI/OCRD-12, Typical Repository Conditions for Generic Commercial and Defense High-Level Nuclear Waste and Spent Fuel Repositories in Crystalline Rock

BMI/OCRD-12 is being reissued as BMI/OCRD-12 (Rev. 1) in order to incorporate changes necessary to replace information no longer considered applicable. The revised material is within the Executive Summary (text on page vii, Table ES-3 on page viii) and in Chapter 5 (pages 14, 15, 16, and 17). A bibliography (page 26) has been added to provide further reference material for the reader.

A A Bauer

Arthur A. Bauer
Engineering Technology
Department

AAB:mb

BMI/OCRD-12 (Rev. 1)
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The content of this report was effective as of September 1982. The content of the revised sections was effective as of November 1985. This report was prepared by Battelle Project Management Division, Office of Nuclear Waste Isolation and Office of Crystalline Repository Development under Contract Nos. DE-AC06-76RLO1830 and DE-AC02-83CH10139 with the U.S. Department of Energy.

## ABSTRACT

This report summarizes activities to determine conditions for temperature, pressure, fluid, chemical, and radiation environments typical of those that may be expected to exist in commercial and defense high-level nuclear waste and spent fuel repositories in crystalline rock*. These conditions were generated by the Reference Repository Conditions Interface Working Group (RRC-IWG), an ad hoc IWG established by the National Terminal Storage (NWTS) Program's Isolation Interface Control Board (I-ICB).**

The repository conditions are based on the standard room-and-pillar mined repository concept with waste emplaced in vertical holes drilled in the room floor.

Some important results obtained are given below for the selected local areal thermal loadings of 20, 25, and 13.5 W/m$^2$ for spent fuel (SF), commercial high-level waste (CHLW), and defense high-level waste (DHLW), respectively. In all cases, the results below are given in order for SF, CHLW, and DHLW. Some thermal results are: maximum waste temperature - 190, 225, and 120 C; maximum rock temperature - 150, 165, and 105 C. The length of time for significant thermal exposure is greater for SF than the other wastes. Vapor phase pressures are not expected to rise significantly above atmospheric until the repository is sealed. After sealing, the water pressure inside the sealed excavations will gradually increase to the local hydrostatic head. A generic crystalline rock ground-water composition and expected gamma radiation dose rates are also provided in the report.

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*In the DOE Crystalline Repository Project, the term crystalline rocks are defined as intrusive igneous and high-rank metamorphic rocks rich in silicate minerals with a grain size sufficiently coarse that individual materials can be distinguished with the unaided eye.

**The DOE National Waste Terminal Storage Program has since become the Civilian Radioactive Waste Management Program.

## EXECUTIVE SUMMARY

This report summarizes activities to determine conditions for temperature, pressure, fluid, chemical and radiation environments typical of those that may be expected to exist in commercial and defense high-level nuclear waste and spent fuel repositories in crystalline rock. These conditions were generated by the Reference Repository Conditions Interface Working Group (RRC-IWG), an ad hoc IWG established by the National Waste Terminal Storage Program's (NWTS) Isolation Interface Control Board (I-ICB).* The most recent members of the RRC-IWG were:

G.E. Raines, Office of Nuclear Waste Isolation (ONWI), Chairman

N.E. Bibler, Savannah River Laboratory (SRL), Defense High-Level Waste

H.C. Claiborne, Oak Ridge National Laboratory (ORNL), Salt Repository Environment

K.H. Henry, Rockwell Basalt Waste Isolation Project (BWIP), Basalt

J.B. Moody, Office of Nuclear Waste Isolation (ONWI), Geochemical Environment

R.V. Matalucci, Sandia National Laboratories (SNL) (WIPP), Salt Repository Environment

R.H. Zimmerman, Sandia National Laboratories (SNL), Nevada Nuclear Waste Storage Investigations (NNWSI), Tuff Repository Environment

J. L. McElroy, Pacific Northwest Laboratory (PNL)

J. D. Osnes, RE/SPEC Inc. (RE/SPEC)

L.D. Rickertsen, Science Applications, Inc. (SAI).

Previous membership on this Committee included:

G.D. Callahan, RE/SPEC

K.R. Hoopingarner, Rockwell

N. Hubbard, ONWI

T.O. Hunter, SNL

R.W. Lynch, SNL

M.H. Tennant, SRL

*The NWTS Program has since been replaced by the Civilian Radioactive Waste Management (CRWM) Program.

The repository conditions presented in this report are intended to serve as a guide for: (a) scientists conducting material performance tests; (b) engineers preparing the design of repositories; (c) the technically conservative conditions to be used as a basis for DOE license applications; and (d) scientists and engineers developing waste forms.

In addition to the above purposes, these repository conditions can be used as typical conditions for evaluating the relative performance of the various candidate sites.

Utilization of the conditions described herein resulted in a technically conservative repository design concept. However, prudence must be exercised in using the room-and-pillar dimensions for the reference repository in a site specific design, since the site rock mass strength properties, depth and geometry will probably differ from the values assumed in this design concept.

Three types of waste were considered in this effort: spent fuel (SF) from light water reactors, commercial high-level waste (CHLW) that would result from reprocessing of light water reactor fuel, and defense high-level waste (DHLW). Pressurized water reactor (PWR) spent fuel was chosen over Boiling Water Reactor (BWR) spent fuel as a reference because of its greater thermal impact. CHLW resulting from a 3:1 mix of wastes from fresh $UO_2$ and mixed oxide (MOX) fuels was chosen as a reference case. DHLW planned for processing by Savannah River Laboratory was chosen over other lower heat-generating defense wastes. Reference ages chosen for emplacement were 10, 10, and 15 years out-of-reactor for SF, CHLW, and DHLW, respectively. These ages are about as low as could reasonably be available for geologic disposal. Reference heat generation rates are 0.55, 1.0, and 0.31 kW per package at emplacement. A simplified package was assumed consisting of a single canister containing either 1 PWR spent fuel assembly or waste contained in borosilicate glass for CHLW and DHLW with dry crushed rock as backfill for SF and DHLW and dry crushed bentonite as backfill for CHLW.

While other emplacement concepts are being considered for a repository in crystalline rock the bases selected for calculation of the repository conditions in this study are illustrated in Table ES-1. These descriptions are based on a standard room-and-pillar mined repository concept with storage rooms excavated deep in the rock and vertical emplacement holes drilled in the floor in rows. Waste packages are emplaced in the holes and the holes are then backfilled and plugged with a concrete or other shielding plug.

Repository thermal conditions are given in Table ES-2. The relatively low thermal loading of the large DHLW canister results in very benign conditions even with the relatively small distances separating waste packages that were used here. SF and CHLW canisters are spaced to result in temperatures that are not anticipated to cause problems.

The vapor pressure in the emplacement hole is not expected to rise significantly above the ambient air pressure at the repository horizon because the reference repository has no provision for sealing the emplacement holes from the emplacement rooms. Hence, any vapor in the emplacement hole communicates freely with the room which communicates with the atmosphere through ventilation and haulage shafts during the operational period. Even if a provision for plugging the emplacement hole were made, it is unlikely that the hole would be sealed from the room because of the fractures and joints present in crystalline rocks, some of which would probably extend from the emplacement hole through the rock mass to the room.

In the isolated case where a plugged emplacement hole would not have a fracture or joint intercepting it and the emplacement room, the maximum possible vapor pressure would correspond to the saturation pressure at the maximum canister surface temperature. This is clearly an overprediction, but is an understandable upper limit for vapor pressure. This pressure peaks after about 8 years at about 1.8 MPa, 20 years at about 0.8 MPa, and 20 years at about 0.2 MPa for CHLW, SF, AND DHLW respectively. Values at 25 years (a minimum operational period) will be about 1.3 MPa for CHLW and remain at near peak values for SF and DHLW.

Mine water pumping would cease and flooding of the backfilled underground excavations would begin after the operational period. As the excavations flood, the pressure in the emplacement holes would rise due to the increasing hydraulic head until the local hydrostatic head is

TABLE ES-1. REFERENCE CRYSTALLINE ROCK REPOSITORY CHARACTERISTICS

| Characteristics | CHLW | DHLW | SF |
|---|---|---|---|
| Repository Configuration | | | |
| Areal Extent | (a) | (a) | (a) |
| Thermally Loaded Area | (b) | (b) | (b) |
| Depth Below Surface (m) | 1000 | 1000 | 1000 |
| Thermal Loading (at emplacement) | | | |
| Local Areal Thermal Loading ($W/m^2$) | 25. | 13.5 | 20. |
| Average Areal Thermal Loading ($W/m^2$) | <25. | <13.5 | <20. |
| Room Description | | | |
| Room Length (m) | Very Long | Very Long | Very Long |
| Room Width (m) | 7.5 | 7.5 | 7.5 |
| Room Height (m) | 7.0 | 7.0 | 7.0 |
| Adjacent Pillar Thickness (m) | 22.5 | 22.5 | 22.5 |
| Canister Emplacement Holes | | | |
| Rows per Room | 2 | 2 | 2 |
| Row Separation (m) | 2.5 | 2.5 | 2.5 |
| Hole Pitch (along row) (m) | 2.67 | 1.53 | 1.83 |
| Hole Depth (m) | 5.0 | 5.0 | 6.7 |
| Hole Diameter (m) | 0.524 | 0.810 | 0.556 |
| Canisters per Hole | 1 | 1 | 1 |

(a) Near-field conditions near the center of a large repository are not significantly dependent on the overall size. The near-field conditions near the repository center are described in this report. Conditions near the outer edges would not be as severe as near the center. Thus, the areal extent need not be specified for the purposes of this report.

(b) Note (a) applies. In addition, this area will be less than the areal extent because of haulage ways and shaft pillars within the repository.

TABLE ES-2. REPOSITORY THERMAL CONDITIONS FOR CRYSTALLINE ROCK

| | SF | CHLW | DHLW |
|---|---|---|---|
| Local Areal Thermal Loading, $W/m^2$ (kW/Acre) | 20(80) | 25(100) | 13.5(55) |
| Resultant Conditions | | | |
| Waste Peak Temperature, C | 190 | 225 | 120 |
| Time of Occurrence, yr | 7 | 5 | 15 |
| Temperature at 100 years, C | 145 | 105 | 75 |
| Canister Surface | | | |
| Peak Temperature, C | 170 | 205 | 115 |
| Time of Occurrence, yr | 25 | 8 | 20 |
| Temperature at 100 years, C | 140 | 110 | 75 |
| Rock | | | |
| Peak Temperature, C | 150 | 165 | 105 |
| Time of Occurrence, yr | 35 | 15 | 25 |
| Temperature at 100 years, C | 130 | 100 | 70 |

reached. Although the flooding rate has not been predicted, it is expected that underground excavations in crystalline rocks will completely fill within a couple of decades after the operational period.

As the underground excavations fill, no boiling or vaporization can occur if the hydraulic head exceeds the saturation pressure at the maximum canister surface temperature. For pressures given and the reference repository depth of 1000 m, no further vaporization will occur after the underground excavations have filled, if the distance from the water table surface to the repository horizon is at least 135 m.

Crystalline rock ground-water compositions for reference use are given in Table ES-3. The compositions are applicable to waters found near the ground surface and also at a depth of 800 m. Any effects of the corrosion of package materials are not included.

TABLE ES-3. CHEMISTRY OF CRYSTALLINE-ROCK GROUND WATERS

| | Content, mg/L | |
|---|---|---|
| Ionic Species | Near-Surface | 800-m Depth |
| $Ca^{+2}$ | 20 | 2,800 |
| $Mg^{+}$ | 2 | 150 |
| $Na^{+}$ | 10 | 2,500 |
| $K^{+}$ | 1 | 20 |
| $Sr^{+2}$ | -- | 50 |
| $SiO_2$ | 15 | 6 |
| Fe (total) | 0.5 | 5 |
| $Mn^{+2}$ | 0.1 | 0.5 |
| $HCO_3^{-}$ | 40 | 25 |
| $SO_4^{-2}$ | 4 | 500 |
| $Cl^{-}$ | 30 | 9,000 |
| $F^{-}$ | 1 | 2 |
| $Br^{-}$ | -- | 100 |
| $PO_4^{-2}$ | 0.03 | 0.3 |
| $NO_3^{-}$ | 0.2 | 0.2 |
| pH | 7.0 | 8.0 |
| Eh | 0.0V | -0.25V |

Gamma radiation dosages have been calculated for SF and CHLW packages. Maximum absorbed doses in the rock mass after 10,000 years are of the order of $10^9$ and $10^{10}$ rads for SF and CHLW respectively. Maximum dose rates are about $4 \times 10^3$ and $5 \times 10^4$ rads/hr for SF and CHLW respectively.

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# 1 INTRODUCTION

The temperature, pressure, fluid, chemical, and radiation environments that are expected to exist in commercial and defense high-level nuclear waste and spent fuel repositories under normal conditions are being determined. This report does not deal with current reference waste package, design and emplacement concepts for a repository in crystalline rock or with specific sites, but using generic information for crystalline rock, describes approximate repository conditions, typical of those that can be expected.

This report considers repositories in crystalline rocks for these types of nuclear waste: (1) high-level waste that would result from the reprocessing of spent fuel from light water reactors (CHLW), (2) high-level waste reprocessing spent fuel from defense reactors (DHLW), and (3) the spent fuel (SF) from light water reactors. The report deals only with normal operation conditions. Two earlier reports provide the basis for the generic conditions assumed. The technical basis for these conditions and most of the specific conditions are taken from Reference 1. The primary constraint considered for determining conditions for a CHLW, DHLW, or SF repository in crystalline rock was conservatism based on the Interagency Review Group (RG) report recommendation contained in Reference 2.

The Reference Repository Conditions Interface Working Group (RRC-IWG) was an ad hoc Interface Working Group (IWG) established by the Isolation Interface Control Board (I-ICB). The I-ICB was one of the Interface Control Boards established by the Department of Energy (DOE) to achieve interface definition and provide control among the various waste management programs. The I-ICB, by design, was to also provide the mechanism to achieve interface definition and control among the various waste isolation programs, i.e., Office of Nuclear Waste Isolation (ONWI), Basalt Waste Isolation Project (BWIP), the Nevada Nuclear Waste Storage Investigations (NNWSI), the Subseabed Disposal Program, and the Waste Isolation Pilot Plant (WIPP). The I-ICB established a number of Interface Coordination Groups (ICG) to assist in its mission. The charter also permitted the establishment of ad hoc (temporary) IWGs as needed for special duties. The RRC-IWG was established with the following responsibilities:

(1) Define and recommend National Waste Terminal Storage (NWTS) Reference Repository Conditions to the I-ICB using Expected Repository Environment (ERE) reports and other information sources.

(2) Keep ERE subcontractors appraised of status of the many bases required for their work and recommend necessary changes in bases being used.

(3) Recommend programmatic guidance for the ERE subcontractors to ERE project monitors.

(4) Recommend additional projects to the I-ICB, if any, required to provide sufficient information for adequate definition of Reference Repository Conditions.

(5) Review Draft ERE reports.

Membership on the Committee has changed during the preparation of this report. The most recent members of the RRC-IWG were:

G.E. Raines, ONWI, Chairman
N.E. Bibler, SRL (Defense High-Level Waste)
N.E. Claiborne, ORNL (ERE-Salt)
K.H. Henry, Rockwell (BWIP)
J.B. Moody, ONWI
R.V. Matalucci, Sandia (WIPP)
R.H. Zimmerman, Sandia (NNWSI)
J.L. McElroy, PNL
J.D. Osnes, RE/SPEC (ERE-granite)
L.D. Rickertsen, SAI.

Each of the most recent RRC-IWG members is a coauthor of this report. Previous membership on this IWG included:

G.D. Callahan, RE/SPEC
K.R. Hoopingarner, Rockwell
N. Hubbard, ONWI
T.O. Hunter, SNL
R.W. Lynch, SNL
M.H. Tennant, SRL

## 2 REFERENCE REPOSITORY CHARACTERISTICS

The reference repository characteristics are based on a synthesis of existing conceptual and generic designs for crystalline rock repositories from throughout the world. The characteristics are defined only to the extent which is necessary to predict the various expected conditions described in this report. Throughout the definition of reference repository characteristics and subsequent analyses based on these characteristics, technical conservatism was maintained by utilization of the recommendations contained in Reference 2.

The reference repository design for the three waste types considered is a single-level design located at a depth of 1000 m. The repository is of room-and-pillar construction with vertical emplacement holes for one waste package in two parallel rows along the length of the emplacement rooms. The relevant characteristics for the reference repositories are summarized in Table 1.

The local areal thermal loadings are 25 $W/m^2$ (100 kW/acre) for CHLW, 1.35 $W/m^2$ (55 kW/acre) for DHLW, and 20 $W/m^2$ (80 kW/acre) for SF. Because of passive regions (shafts, corridors, etc.), the overall loadings of the repositories will average less than these local values. However, since detailed repository designs do not exist, the overall thermal loadings will be assumed to be the same as the local loadings.

TABLE 1. REFERENCE CRYSTALLINE ROCK REPOSITORY CHARACTERISTICS

| Characteristics | CHLW | DHLW | SF |
|---|---|---|---|
| **Repository Configuration** | | | |
| Areal Extent | (a) | (a) | (a) |
| Thermally Loaded Area | (b) | (b) | (b) |
| Depth Below Surface (m) | 1000 | 1000 | 1000 |
| **Thermal Loading (at emplacement)** | | | |
| Local Areal Thermal Loading ($W/m^2$) | 25. | 13.5 | 20. |
| Average Areal Thermal Loading ($W/m^2$) | <25. | <13.5 | <20. |
| **Room Description** | | | |
| Room Length (m) | Very Long | Very Long | Very Long |
| Room Width (m) | 7.5 | 7.5 | 7.5 |
| Room Height (m) | 7.0 | 7.0 | 7.0 |
| Adjacent Pillar Thickness (m) | 22.5 | 22.5 | 22.5 |
| **Canister Emplacement Holes** | | | |
| Rows per Room | 2 | 2 | 2 |
| Row Separation (m) | 2.5 | 2.5 | 2.5 |
| Hole Pitch (along row) (m) | 2.67 | 1.53 | 1.83 |
| Hole Depth (m) | 5.0 | 5.0 | 6.7 |
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| Canisters per Hole | 1 | 1 | 1 |

(a) Near-field conditions near the center of a large repository are not significantly dependent on the overall size. The near-field conditions near the repository center are described in this report. Conditions near the outer edges would not be as severe as near the center. Thus, the areal extent need not be specified for the purposes of this report.

(b) Note (a) applies. In addition, this area will be less than the areal extent because of haulage ways and shaft pillars within the repository.

## 3 WASTE PACKAGE CHARACTERISTICS

The characteristics of the waste packages, for which studies were conducted, are given in Table 2. In the reference repository designs considered, the emplacement hole is unlined. Immediately after the waste canister is emplaced, the 0.1 m annulus between the canister and the emplacement hole and the remaining 2 m of emplacement hole above the canister are backfilled.

In the DHLW and the SF repositories, the backfill material is dry, crushed rock. The thermal conductivity of the backfill is assumed to be approximately 10 percent of the thermal conductivity of the intact rock. This is a conservative estimate for the thermal conductivity of dry, crushed aggregate. The thermal conductivity may be greatly enhanced by the presence of a small amount of moisture or by the choice of an alternate backfill material.

Because of the higher thermal loading of the CHLW canister, a backfill material with higher thermal conductivity was required in order to reduce canister skin temperatures to an acceptable range. The backfill material chosen was dry bentonite which typically has a thermal conductivity of approximately 0.5 W/m-K (twice the conductivity of dry, crushed granite). Because clays like bentonite swell and close voids when they absorb moisture, this may be regarded as a technically conservative estimate of the thermal conductivity.

The relative heat generation rates of the three waste types are given in Table 3. The decay characteristics for the SF and the CHLW were selected from the fuel cycles considered in the Generic Environmental Impact Statement (GEIS) for nuclear waste repositories and the characteristics for the DHLW were provided by Savannah River Laboratories (SRL). The decay characteristics of CHLW and DHLW differ from SF primarily because CHLW and DHLW contain much less plutonium (a long-lived isotope) than SF.

TABLE 2. WASTE PACKAGE CHARACTERISTICS

| Characteristics | SF | DHLW | CHLW |
|---|---|---|---|
| **Waste Description** | | | |
| Active Length (m) | 3.7 | 2.3 | 2.4 |
| Active Volume ($m^3$) | NA | 0.63 | 0.18 |
| Age of Waste (years)[a] | 10 | 15 | 10 |
| Thermal Loading (kW/canister)[a] | 0.55[b] | 0.31 | 1.0 |
| Mass Loading (MTHW equivalent) | 0.46 | NA | 1.0 |
| **Canister Dimensions** | | | |
| Outer Diameter (cm) | 35.6[d] | 61.0 | 32.4[c] |
| Inner Diameter (cm) | 33.7 | 59.1 | 30.5 |
| Length (m) | 4.7 | 3.0 | 3.0 |
| **Backfill Dimensions** | | | |
| Thickness (cm) | 10. | 10. | 10. |
| Length (m) | 6.7 | 5.0 | 5.0 |
| **Materials** | | | |
| Waste | $UO_2$[(e)] | Glass[(e)] | Glass[(e)] |
| Filler in Canister | Helium | Air | Air |
| Canister | CS | SS | SS |
| Backfill | CR | CR | Bt |

(a) At emplacement (after discharge from reactor).

(b) Heat generation rate for a single PWR assembly 10 years out-of-reactor. A similar size package of BWR assemblies would generate less power 10 years out-of-reactor, but the value for PWR assemblies has been chosen to predict maximum temperatures in the repository.

(c) Nominal 12" Schedule 40s pipe.

(d) Nominal 14" Schedule 30 pipe.

(e) The choice of waste form for these calculations was based on their advanced state of engineering development. The calculated environments outside the waste forms are insensitive to the details of the waste forms themselves other than heat output and physical dimensions.

NA = Not Applicable
SS = 304L Stainless Steel
CS = Carbon Steel
Bt = Bentonite
CR = Crushed Rock

TABLE 3. RELATIVE HEAT-GENERATION RATES

| Year After Emplacement[a] | SF[b] | CHLW[b] | DHLW[c] |
|---|---|---|---|
| 0 | 1.0 | 1.0 | 1.0 |
| 5 | .838 | .810 | .886 |
| 10 | .750 | .692 | .789 |
| 15 | .681 | .600 | .705 |
| 20 | .622 | .529 | .630 |
| 30 | .525 | .402 | .505 |
| 40 | .449 | .313 | .407 |
| 50 | .387 | .246 | .330 |
| 70 | .301 | .157 | .191 |
| 100 | .238 | .0864 | .128 |
| 190 | .137 | .0296 | .032 |
| 290 | .108 | .0215 | .013 |
| 390 | .0919 | .0163 | .0072 |
| 490 | .0806 | .0145 | .0047 |
| 990 | .0466 | .00810 | .0021 |
| 1990 | .0247 | .00404 | .0013 |
| 5990 | .0148 | .00230 | .0009 |
| 9990 | .0114 | .00175 | .0008 |

(a) Assumes CHLW and SF are 10 years out-of-reactor and DHLW is 15 years out-of-reactor at emplacement.

(b) See Y/OWI/TM-34, Nuclear Waste Projections and Source Term Data for FY 1977 (Reference 3). The CHLW decay rates correspond to waste arising from fuel which is a 3:1 mix of fresh $UO_2$ and MOX fuels.

(c) See DPSTD-77-13-3, Preliminary Technical Data Summary No. 3, E. I. duPont de Nemours and Co (Reference 4).

## 4 THERMAL ENVIRONMENTS

The maximum temperatures at the emplacement hole wall, canister surface, and waste centerline for the reference repositories are shown in Figures 1, 2, and 3. The ambient temperature at the repository horizon (1000 m) is assumed to be 20 C. The literature reports measurements of ambient temperatures at this depth in crystalline rock masses in the range of 17 C to 26 C. However, the effect of this variation on the thermal environments is not considered significant compared to the effects of the variability in other properties such as thermal conductivity.

The maximum host rock (emplacement hole wall) temperature occurs in the CHLW repository and peaks at approximately 165 C at 15 years after emplacement. The maximum temperatures at the emplacement hole wall in the SF and the DHLW repositories reach about 150 C after 35 years and about 105 C after 25 years of emplacement, repsectively. Documentation of the computer codes used in calculation of these values is contained in Reference 10.

Calculated far-field temperatures as a function of time are shown in Figures 4 and 5 for various distances above the planar heat source.

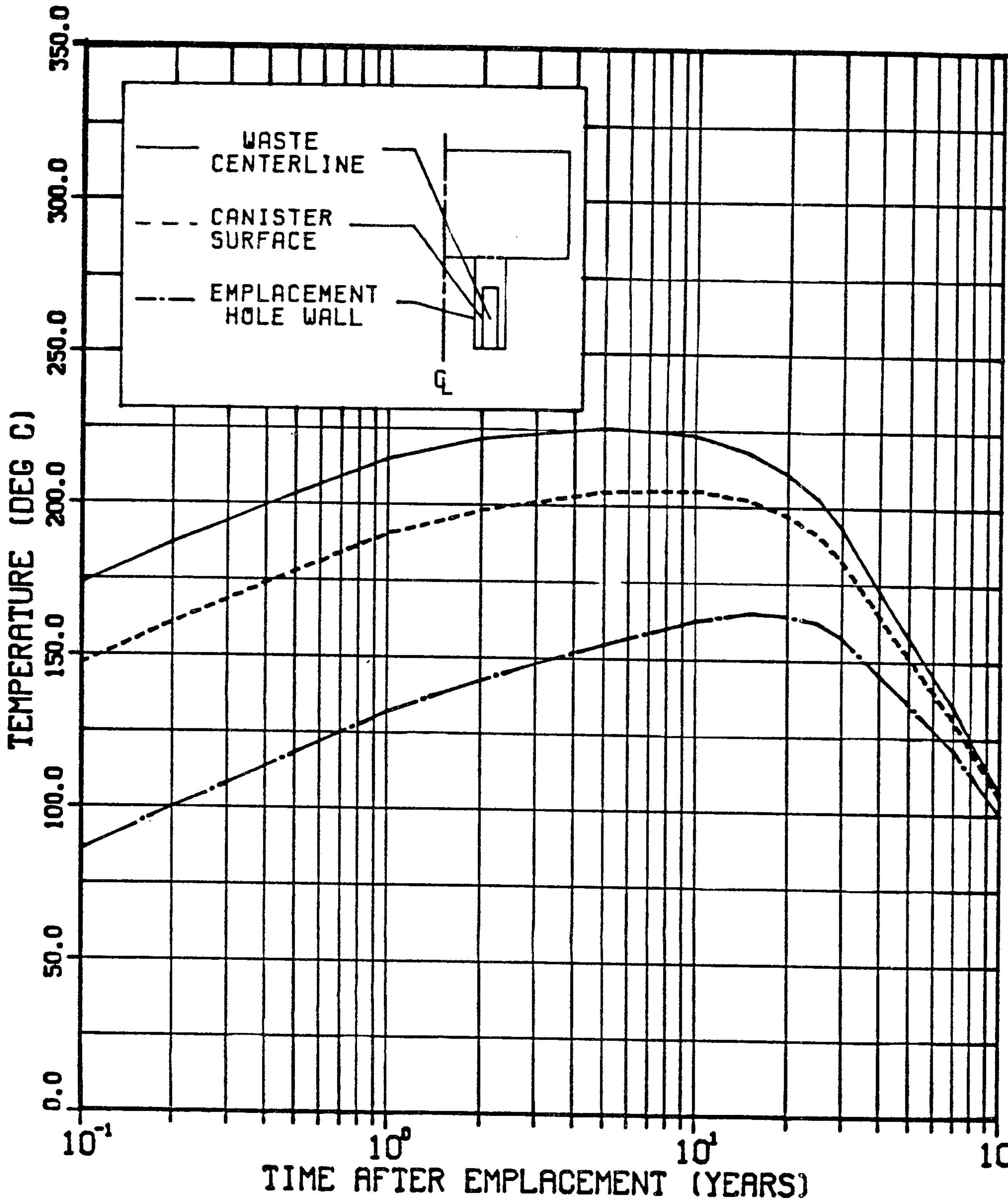


Figure 1. Maximum Temperatures as a Function of Time for a CHLW Repository with Areal Thermal Loadings of 25 $W/m^2$ (1 kW Canister) in Crystalline Rock

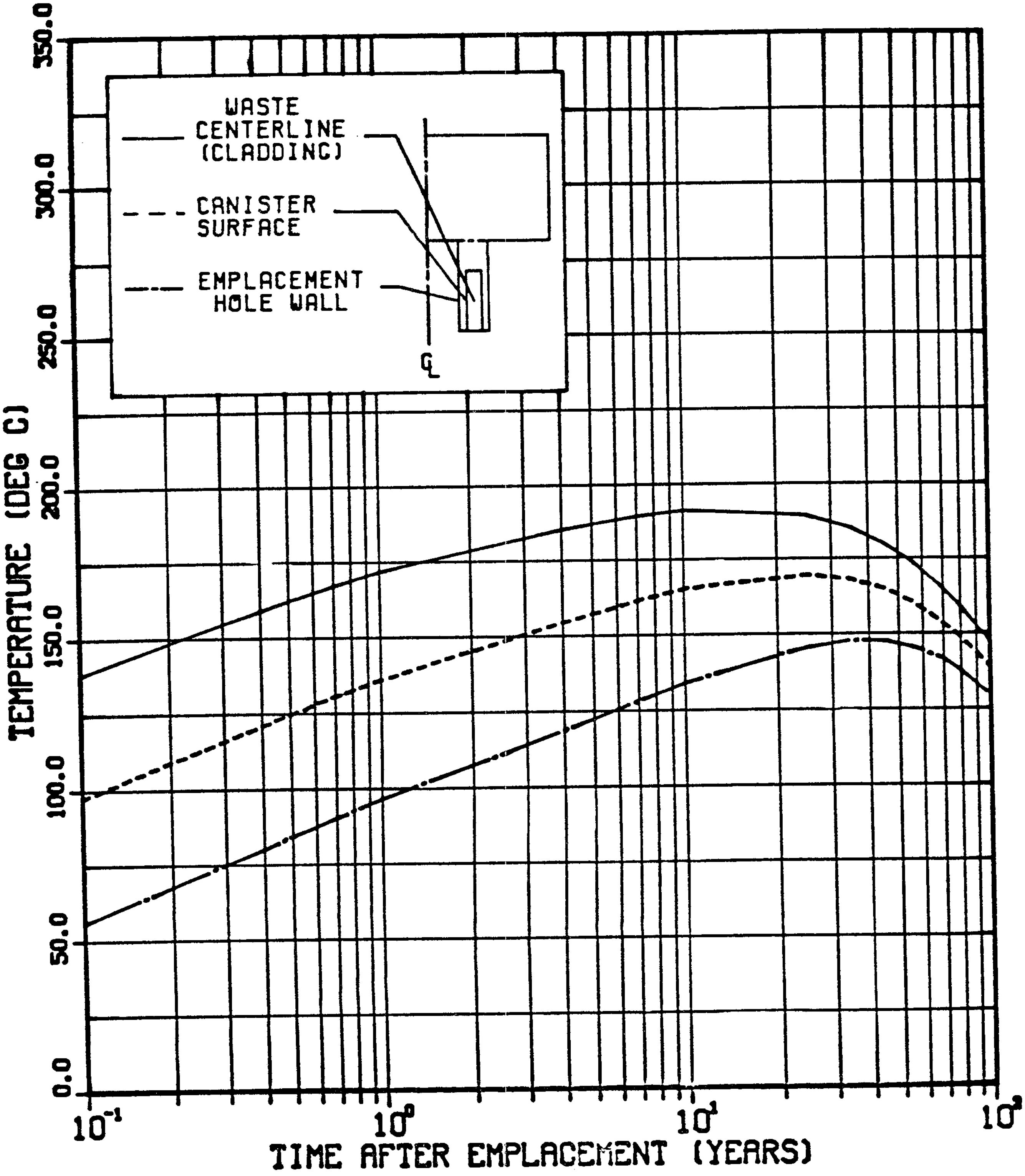


Figure 2. Maximum Temperatures as a Function of Time for a SF Repository with Areal Thermal Loading of 20 W/m$^2$ (550 W Canister) in Crystalline Rock

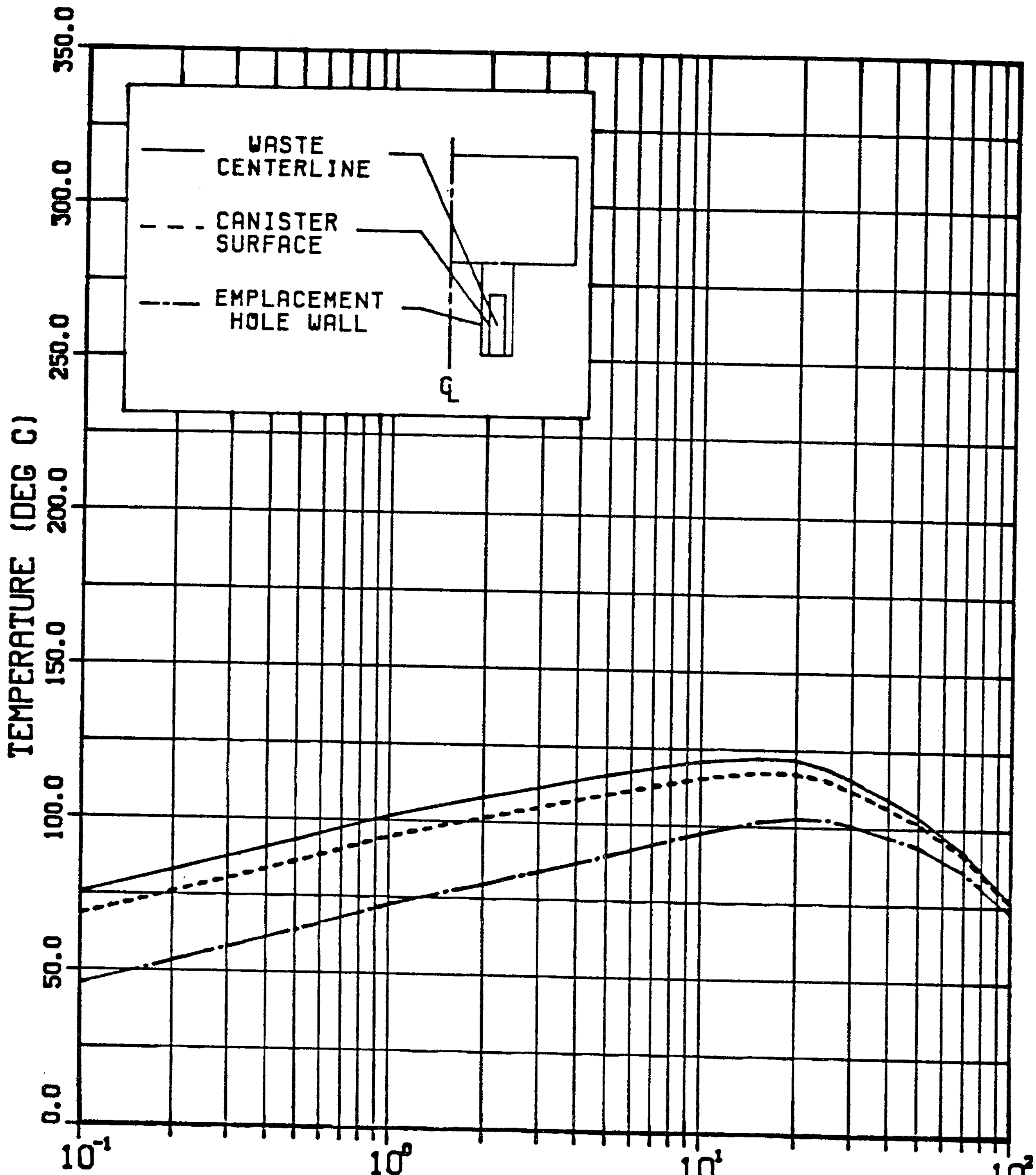


Figure 3. Maximum Temperatures as a Function of Time for a DHLW Repository with an Areal Thermal Loading of 13.5 W/m$^2$ (310 W Canister) in Crystalline Rock

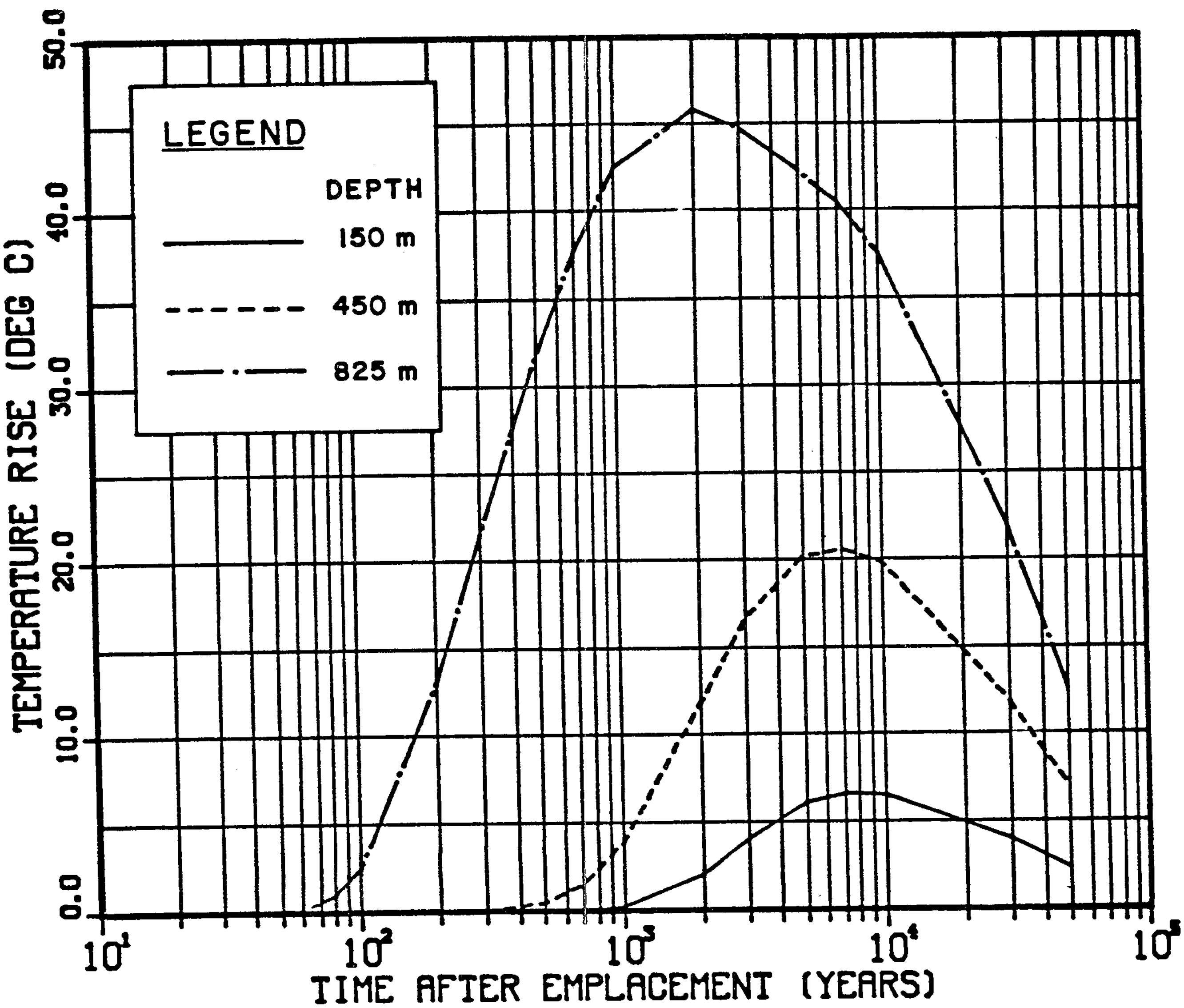


Figure 4. Transient Thermal Response at Several Points Above a SF Repository with an Areal Thermal Loading of 20 W/m$^2$ Located 1000 m Deep in Crystalline Rock

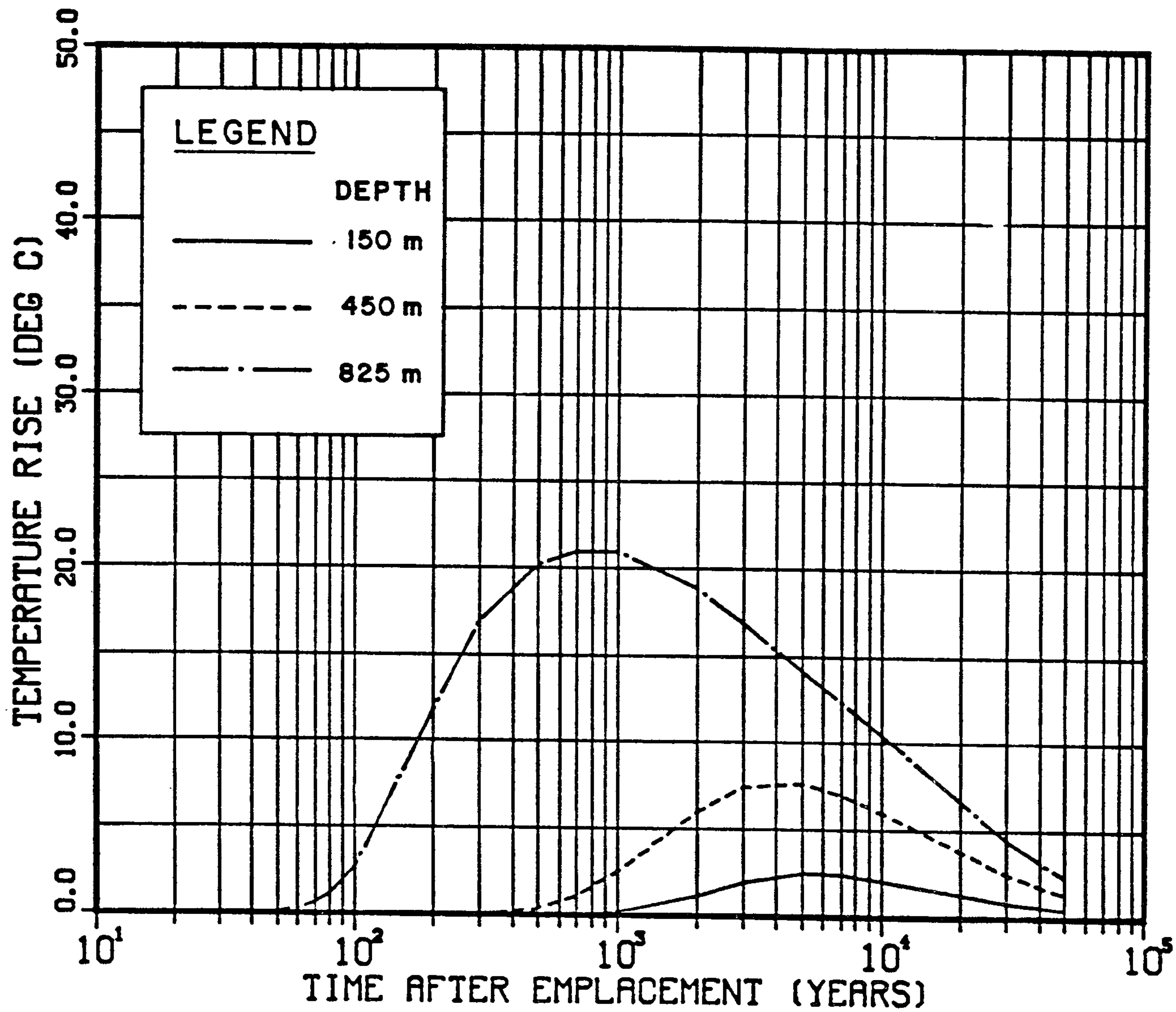


Figure 5. Transient Thermal Response at Several Points Above a CHLW Repository with an Areal Thermal Loading of 25 $W/m^2$ Located 1000 m Deep in Crystalline Rock.

## 5 CHEMICAL ENVIRONMENTS

Crystalline rocks are defined as intrusive igneous and high-rank metamorphic rocks rich in silicate minerals, with a grain size sufficiently coarse that individual minerals can be distinguished with the unaided eye. They may be gneissic or equigranular in character. They can range from acidic to mafic with increasing ferromagnesian content. They include granitic and mafic gneisses in the case of rock of metamorphic origin and, in the case of igneous intrusive rock, granites, granodiorites, syenites, monzonites, and gabbros.

The mineralogical and chemical compositions of crystalline rock are site-specific characterizations. However, the most commonly occurring rock type, in the regions being investigated to identify potential repository sites, is granite, with granodiorite and tonalite following in frequency of occurrence. Consequently, for reference purposes, an average granite chemical composition is shown in Table 4. The associated normative mineralogic content is given in Table 5.

Water contained in bedrock pores at great depth is "very old water" -- water contained in the rock prior to any interactions. This water has been in contact with the minerals in the bedrock for a long time period. Bedrock minerals are in solid phases and do not vary much in composition. Excluding migration from joints and fractures, the water which will seep into a crystalline rock repository from surrounding bedrock will come into chemical equilibrium with the exposed rock. Therefore, the mineral content of the ground water in the repository rock will be dependent upon the composition of the backfill and host rock.

Analyses of crystalline-rock ground waters have been obtained from a variety of locations both within the United States and abroad. Many of the data have been obtained at relatively shallow depths, and data from several of these sources indicate a change in ionic content of the ground waters with depth, leading to waters of higher ionic strength as depth increases.

Perhaps the most useful data are those generated for ground waters from the Canadian Shield, which might be considered representative of waters expected in the North Central Region of the United States and, in general, of

TABLE 4. AVERAGE CHEMICAL COMPOSITION OF GRANITE

| Component | Weight Percent |
|---|---|
| $SiO_2$ | 72.08 |
| $Al_2O_3$ | 13.86 |
| $Fe_2O_3$ | 0.86 |
| FeO | 1.67 |
| MgO | 0.52 |
| CaO | 1.33 |
| $Na_2O$ | 3.08 |
| $K_2O$ | 5.46 |
| $H_2O^+$ | 0.53 |
| $TiO_2$ | 0.37 |
| $P_2O_5$ | 0.18 |
| MnO | 0.06 |

Source: American Geologic Institute, 1982. AGI Data Sheet 44.1

TABLE 5. NORMATIVE MINERALOGICAL CONTENT OF AVERAGE GRANITE

| Mineral | | Chemical Constitution | Normative Percent |
|---|---|---|---|
| Orthoclase | | $KAlSi_3O_8$ | 32.5 |
| Quartz | | $SiO_2$ | 29.4 |
| Albite | Plagioclase | $NaAlSi_3O_8$ | 26.2 |
| Anorthite | Plagioclase | $CaAl_2Si_2O_8$ | 5.5 |
| Ferrosilite | Amphibole | $FeSiO_3$ | 1.8 |
| Hypersthene | Amphibole | $MgSiO_3$ | 1.3 |
| Magnetite | | $Fe_3O_4$ | 1.3 |
| Corundum | | $Al_2O_3$ | 0.9 |
| Ilmenite | | $FeTiO_3$ | 0.7 |
| Apatite | | $Ca_5(PO_4)_3$ | 0.4 |

ground waters in crystalline rock. Based on these data, and supplemented by other information, the ground-water compositions in Table 6 have been constructed for reference purposes. The table shows compositions that might be expected to occur in near-surface crystalline-rock ground waters and in crystalline-rock ground waters at a depth of 800 m.

TABLE 6. CHEMISTRY OF CRYSTALLINE-ROCK GROUND WATERS

| Ionic Species | Content, mg/L Near-Surface | 800 m Depth |
|---|---|---|
| $Ca^{+2}$ | 20 | 2,800 |
| $Mg^{+}$ | 2 | 150 |
| $Na^{+}$ | 10 | 2,500 |
| $K^{+}$ | 1 | 20 |
| $Sr^{+2}$ | -- | 50 |
| $SiO_2$ | 15 | 6 |
| Fe (total) | 0.5 | 5 |
| $Mn^{+2}$ | 0.1 | 0.5 |
| $HCO_3^-$ | 40 | 25 |
| $SO_4^{-2}$ | 4 | 500 |
| $Cl^-$ | 30 | 9,000 |
| $F^-$ | 1 | 2 |
| $Br^-$ | -- | 100 |
| $PO_4^{-2}$ | 0.03 | 0.3 |
| $NO_3^-$ | 0.2 | 0.2 |
| pH | 7.0 | 8.0 |
| Eh | 0.0V | -0.25V |

# 6 RADIATION ENVIRONMENTS

Figures 6, 7, and 8 show the absorbed gamma dose rate in the surrounding crystalline rock as a function of distance from the centerline of the canister for CHLW, SF, and DHLW, respectively. Total absorbed doses for CHLW and SF were found by integrating the dose rates over time at a reference distance of 20.74 cm and at the emplacement hole wall. Because the gamma ray spectrum changes with time, approximate reduction factors were used to convert the dose rates in Figures 6 and 7 to longer decay times. This extrapolation beyond 100 years is a conservative estimate, and the actual absorbed dose would be less than calculated.

Figure 9 shows the total absorbed dose as a function of time found by integrating the dose rates through 10,000 years after emplacement. The total dose absorbed at the reference distance of 20.74 cm after 10,000 years is $7.2(10^9)$ rads and $9.1(10^8)$ rads for the CHLW and the SF canister, respectively. At the emplacement hole wall, the host rock absorbs $3.7(10^9)$ rads and $3.5(10^8)$ rads of gamma radiation after 10,000 years for the CHLW and the SF canisters, respectively. Documentation of the computer codes used in calculating these values is contained in Reference 11.

Although the total absorbed dose is not shown for the DHLW canister, it would be much lower than either the CHLW or the SF canisters because of the more rapid decay and lower radionuclide concentration of the DHLW.

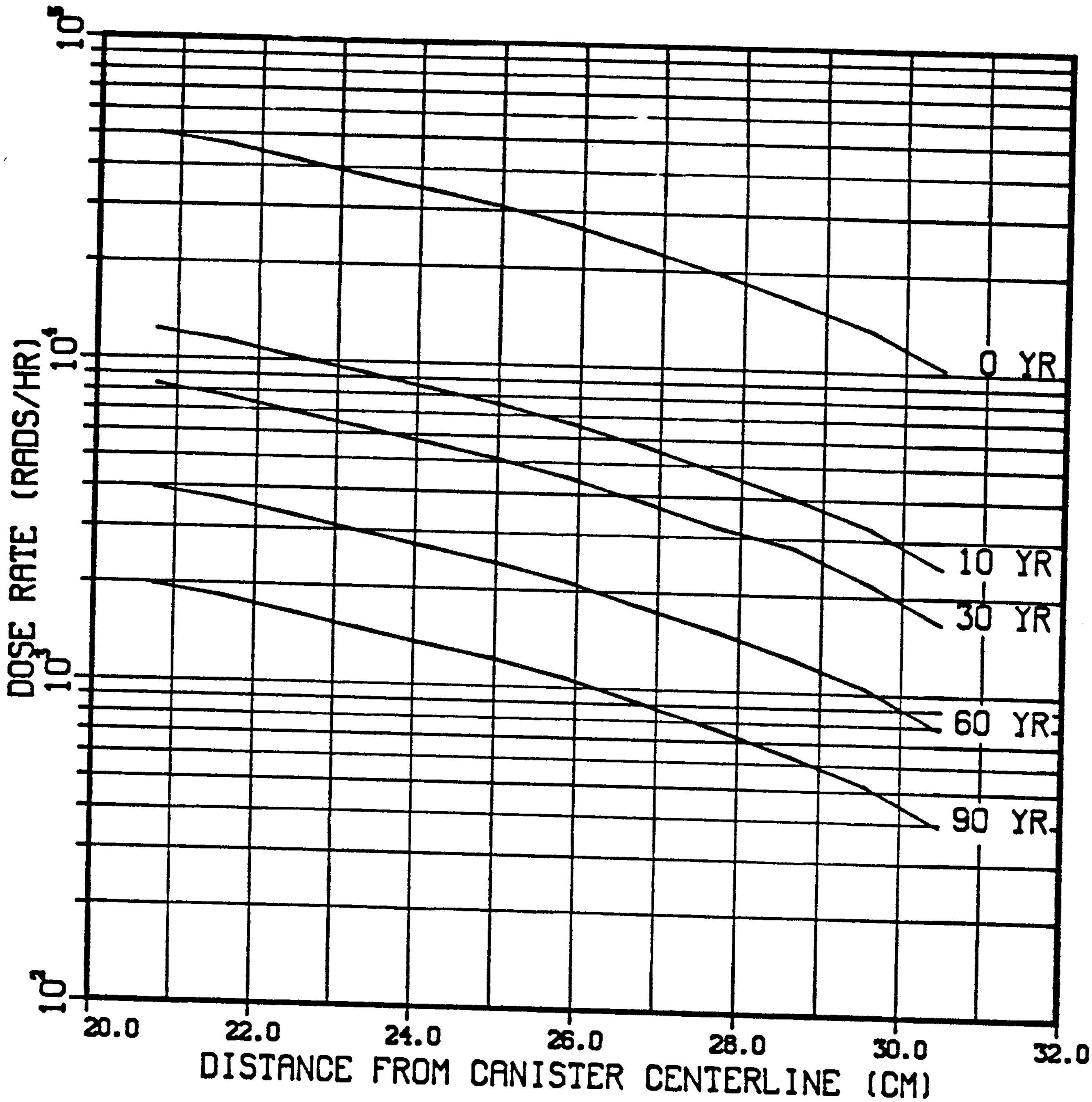


Figure 6. Rate of Gamma Radiation Absorption as a Function of Time after Emplacement of a 1 kW CHLW Canister in Crystalline Rock

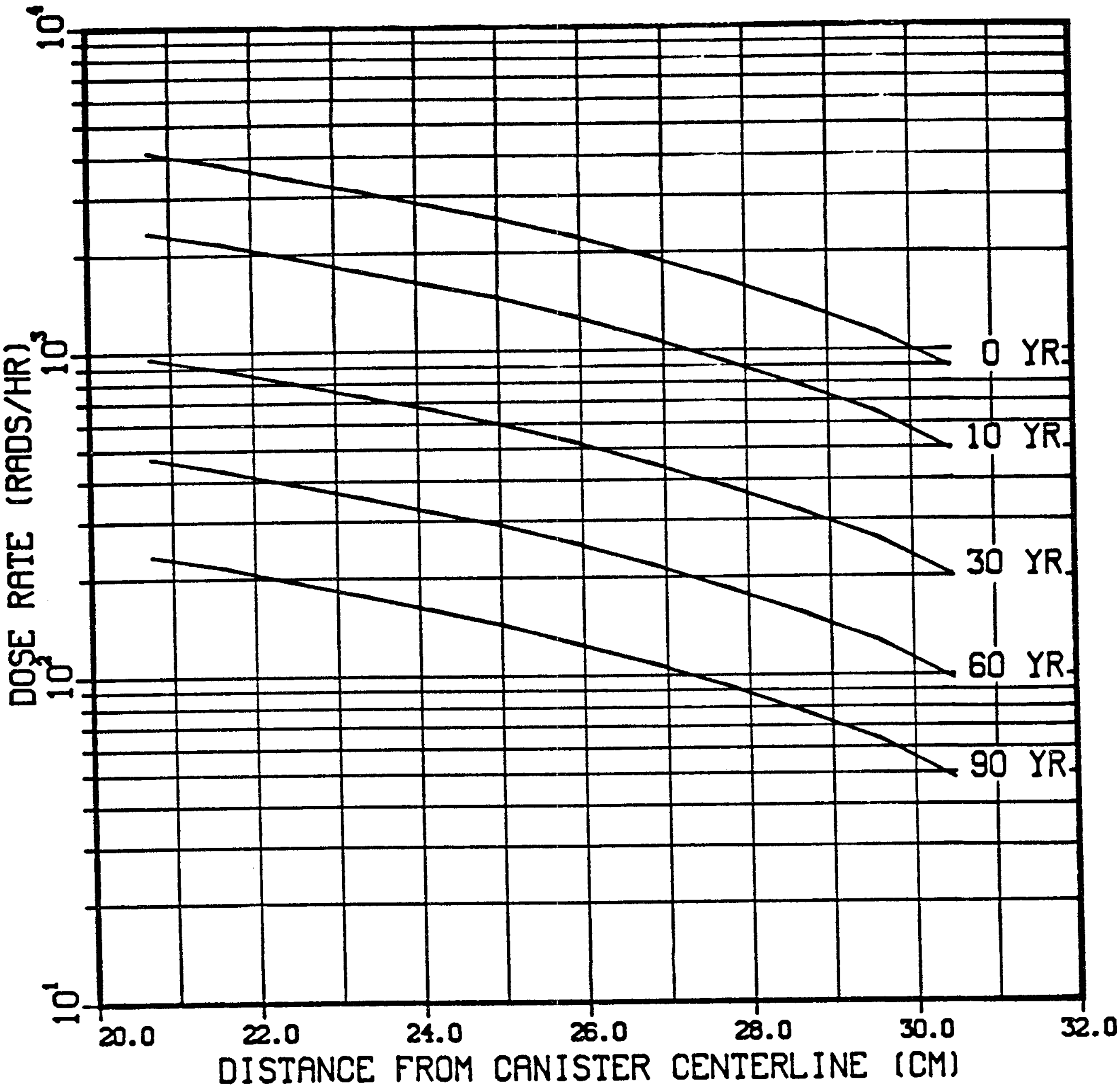


Figure 7. Rate of Gamma Radiation Absorption as a Function of Time Emplacement of 550 W SF Canister in Crystalline Rock

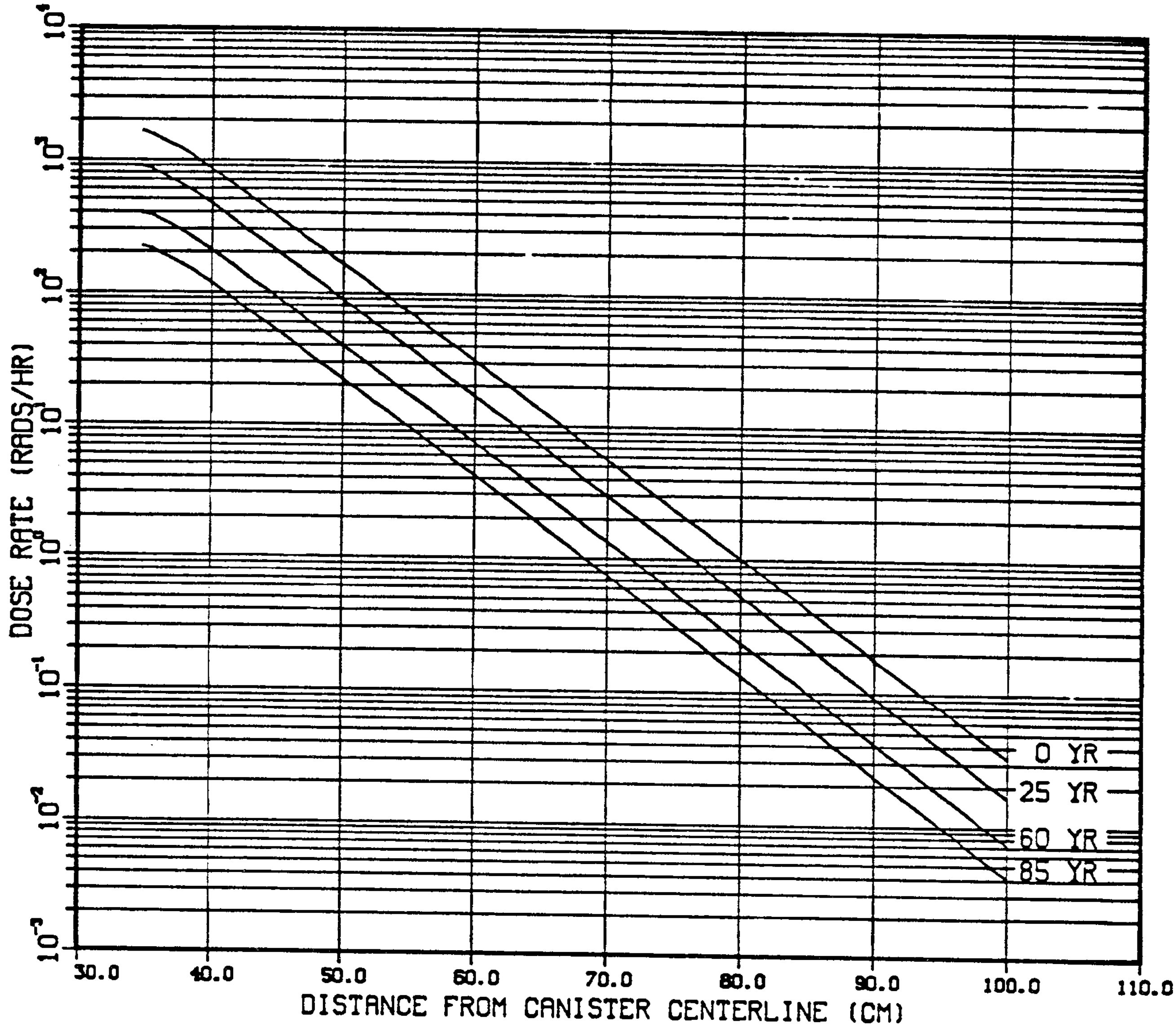


Figure 8. Rate of Gamma Radiation Absorption as a Function of Time after Emplacement of 310 W DHLW Canister in Crystalline Rock

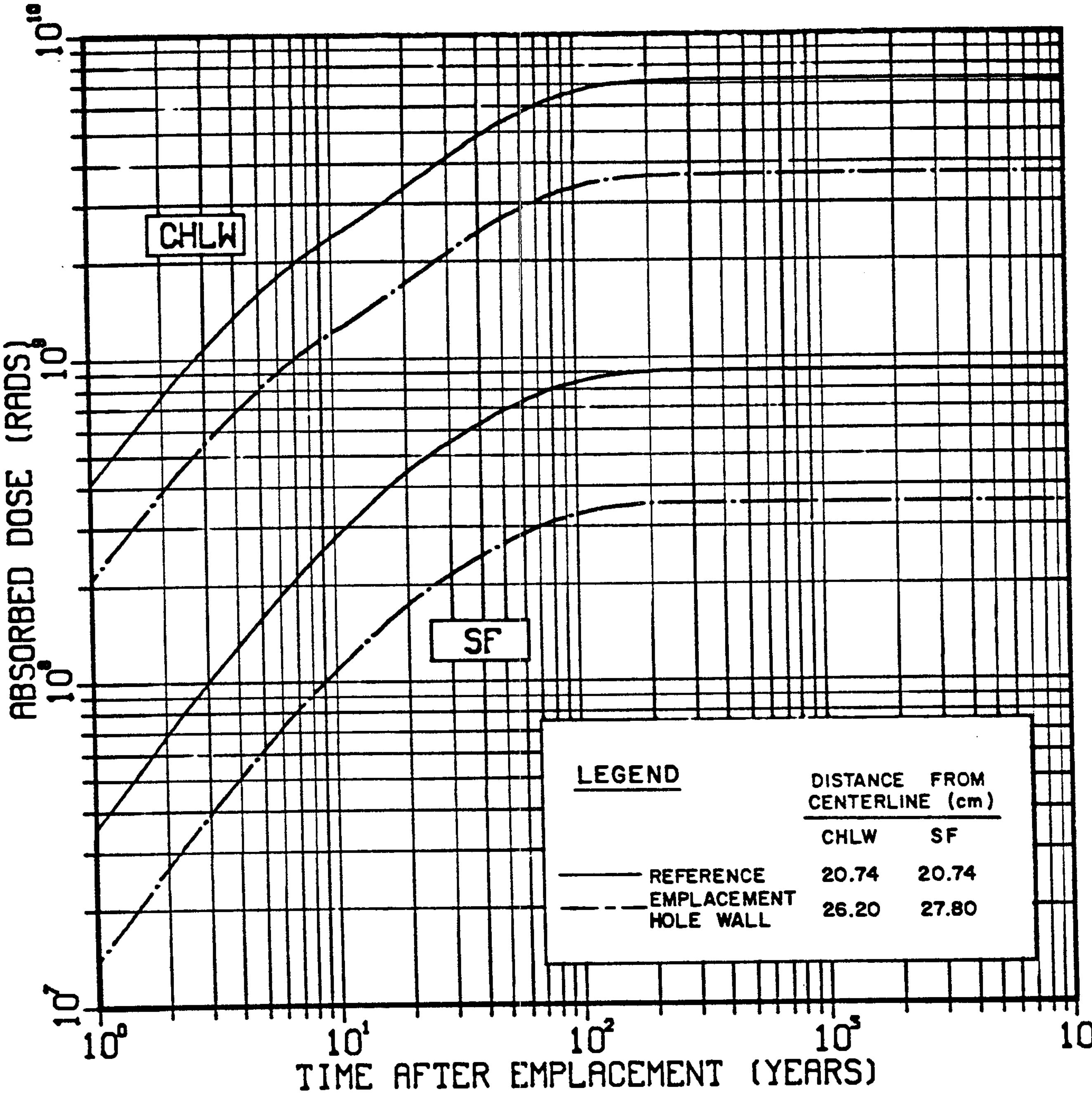


Figure 9. Maximum Cumulative Absorbed Gamma Radiation in Crystalline Rock Surrounding a 1 kW CHLW Canister and a 550 W SF Canister

# 7 VAPOR PRESSURE ENVIRONMENT

The vapor pressure in the emplacement hole is not expected to rise significantly above the ambient pressure at the repository horizon because the reference repository has no provision for sealing the emplacement holes from the emplacement rooms. Hence, any vapor in the emplacement hole communicates freely with the room which communicates with the atmosphere through ventilation and haulage shafts during the operational period. Even if a provision for plugging the emplacement hole were made, it is unlikely that the hole would be sealed from the room because of the fractures and joints present in crystalline rocks, some of which would probably extend from the emplacement hole through the host rock to the room.

In the isolated case where a plugged emplacement hole would not have a fracture or joint intercepting it and the emplacement room, the maximum possible vapor pressure would correspond to the saturation pressure at the maximum canister surface temperature. This is clearly an overprediction, but is an understandable upper limit for vapor pressure. Figure 10 shows the vapor pressure as a function of time assuming a perfectly sealed hole and a vapor pressure corresponding to the saturation pressure of pure water at the maximum canister surface temperature.

Mine water pumping would cease and flooding of the backfilled underground excavations would begin after the operational period. The length of the operational period is not defined, but is expected to be at least 25 years. As the excavations flood, the pressure in the emplacement holes would rise due to the increasing hydraulic head until the local hydrostatic head is reached. Although the flooding rate has not been predicted, it is expected that the underground excavations will completely fill within a couple of decades after the operational period.

As the underground excavations fill, no boiling or vaporization can occur if the hydraulic head exceeds the saturation pressure at the maximum canister surface temperature. As shown in Figure 10, the maximum vapor space pressure that will occur after 25 years (the minimum operational period expected) is in the CHLW repository and is approximately 1.3 MPa (135 m $H_2O$). Therefore, for the reference repository depth of 1000 m, no further vaporization will occur after the underground excavation has filled if the water table is less than 865 m deep (135 m or more above the repository horizon).

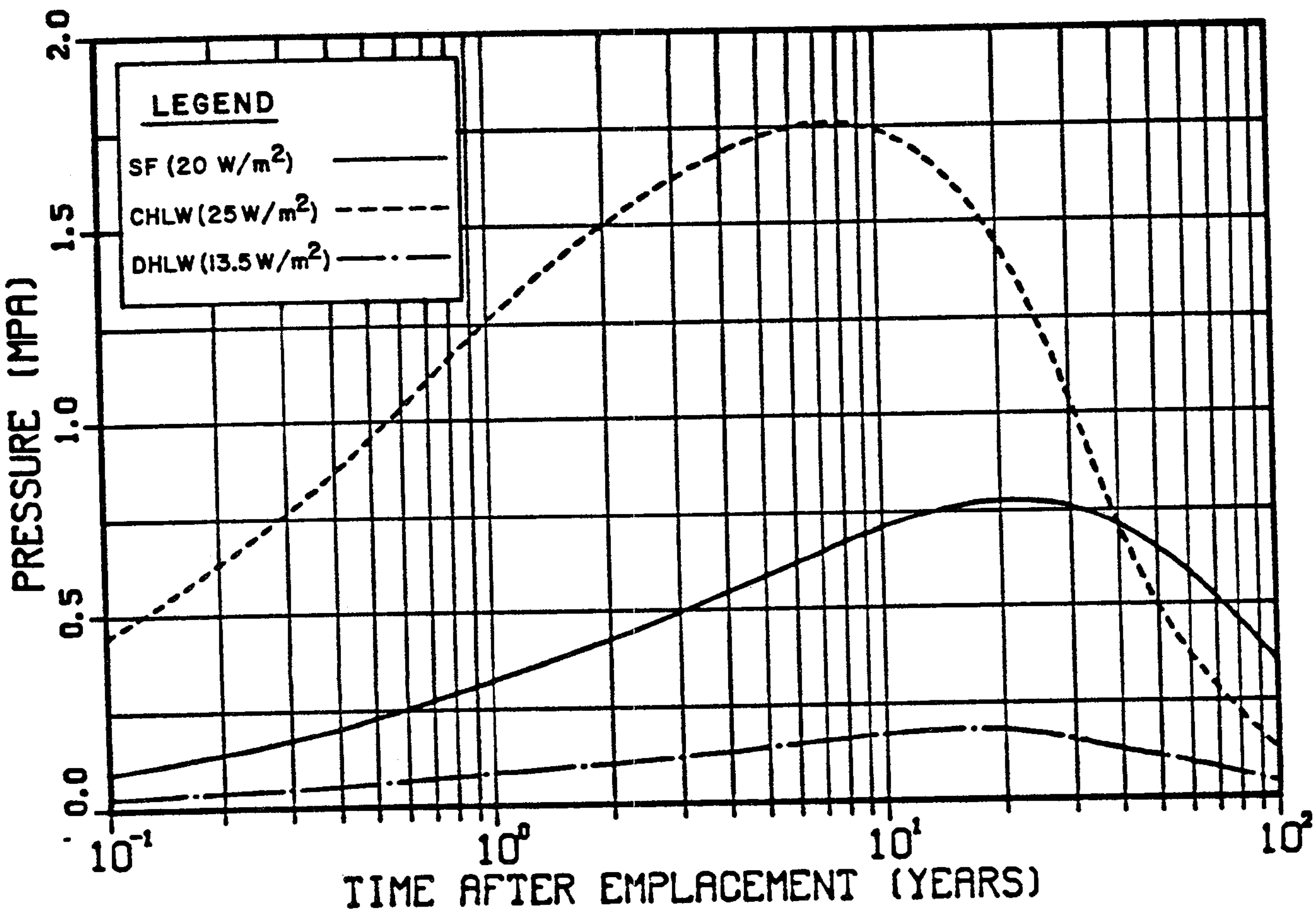


Figure 10. Vapor Space Pressure in a Perfectly Sealed Emplacement Hole in Crystalline Rock

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